LANGLEY GRANT
IN-32-CR
154831
66 P.

THE OHIO STATE UNIVERSITY

RADAR CROSS SECTION STUDIES/COMPACT RANGE RESEARCH

by

W.D. Burnside
A.K. Dominek
I.J. Gupta
E.H. Newman
P.H. Pathak
L. Peters, Jr.

The Ohio State University
ElectroScience Laboratory
Department of Electrical Engineering
Columbus, Ohio 43212

(NASA-CR-183124) RADAR CROSS SECTION STUDIES/COMPACT RANGE RESEARCH Final Report (Ohio State Univ.) 66 p CSCL 17I

N88-26565

Unclas
G3/32 0154831

Final Report No. 716148-31
Grant No. NSG-1613
June 1988

National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23665

N88-26565

50272-101

REPORT DOCUMENTATION PAGE

1. REPORT NO.

2.

3. Recipient's Accession No.

4. Title and Subtitle

RADAR CROSS SECTION STUDIES/COMPACT RANGE RESEARCH

5. Report Date

June 1988

6.

7. Author(s) W.D. Burnside, A.K. Dominek, I.J. Gupta, E.H. Newman, P.H. Pathak and L. Peters, Jr.

8. Performing Organization Rept. No.

716148-31

9. Performing Organization Name and Address

The Ohio State University
ElectroScience Laboratory
1320 Kinnear Road
Columbus, Ohio 43212

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.

(C)

(G) NSG-1613

12. Sponsoring Organization Name and Address

National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23665

13. Type of Report & Period Covered

Final Report

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report represents a summary of the achievements on Grant NSG-1613 between The Ohio State University and the National Aeronautics and Space Administration from May 1, 1987 to April 30, 1988. The major topics associated with this study are as follows:

1. Electromagnetic scattering analysis
2. Indoor scattering measurement systems
3. RCS control
4. Waveform processing techniques
5. Material scattering and design studies
6. Design and evaluation of standard targets, and
7. Antenna studies.

Major progress has been made in each of these areas as verified by the numerous publications.

17. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement

19. Security Class (This Report)

Unclassified

20. Security Class (This Page)

Unclassified

21. No. of Pages

61

22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

TABLE OF CONTENTS

A. INTRODUCTION

The ElectroScience Laboratory has been conducting a general study of evaluating scattered fields. The ultimate goal of this research has been to generate experimental techniques and computer codes of rather general capability that would enable the Aerospace Industry to evaluate the scattering properties of aerodynamic shapes. Another goal involves developing a sufficient understanding of scattering mechanisms so that modification of the vehicular structure could be introduced within constraints set by aerodynamicists. Last but not least, a major goal has been the development of indoor scattering measurement systems with special attention given to the compact range. There has been very substantial progress under Grant NSG 1613 in advancing the state-of-the-art of scattering measurements, control and analysis of the electromagnetic scattering from general targets.

B. PAST ACHIEVEMENTS

1. Electromagnetic Scattering Analysis

After a careful review of the analytic techniques available for handling the scattering from complex targets such as missiles and aircraft, it was very apparent that additional tools were needed. In order to confirm this evaluation, various targets were analyzed and measured to illustrate the magnitude of the problem. It appeared that presently available codes and solutions, although very inefficient in most cases, could be used for most basic shapes. However, as one attempted to shape the target, new mechanisms were needed to be added to

complete the solution but in many cases were not available. Thus, a major effort of this research was to solve these problems.

a. UTD Extensions for Scattering

The general concepts of the basic GTD and scattering analysis have been extended through the advent of the UTD and its extensions which are useful for solving a much broader class of problems. First, the equivalent current concept has been extended by introducing a creeping wave path from the shadow boundary to the diffracting edge. This has been used to obtain much better agreement with experimental data for low level scattering analysis of cones at non-normal incidence. This is quite important for low scattering missile shapes.

Next, the concept of corner diffraction was developed. This has been used to analytically obtain the scattering of certain shapes for which rather high experimental scattering values have been reported elsewhere. This is important in terms of scattering analysis of fins and wings and their control. This will be discussed in the control section later.

We have made a series of measurements for several generations of missile shapes provided by NASA and have obtained excellent agreement between theoretical and experimental results. Experimental patterns have been repeated after various features (such as fins and the RAM-JET engines) were added.

b. Flat Plate Scattering

One of the dominant scatterers on missiles and aircraft takes the form of fins, wings, stabilizers, etc., that can be represented as flat

plates. It has been shown by experiments that the scattering can be controlled by shaping such structures. Since there are examples in the literature of unexplained high scattering from such structures, it becomes important to study such structures quite carefully. A dissertation entitled "UTD Analysis of Electromagnetic Scattering by Flat Plate Structures" by F. Sikta [1] has been completed on this subject. It makes use of the corner diffraction coefficient, the equivalent currents and a novel edge wave analysis based on corner diffraction to treat a variety of plate structures. This includes the development of a solution which predicts the non-principal plane scattered field. This has not been considered by any realistic approach in the past. This analysis not only predicts scattering from such plates, but it should be useful to the designer in two ways: 1) in fixing the shape of the fin, and 2) in establishing the parameters and position of absorber required to reduce the scattered fields.

c. Physical Optics Correction

The physical optics (PO) solution has been known for many years to be an approximate solution. In fact, the physical theory of diffraction (PTD) is an addition to PO which makes it more correct in terms of scattering from edge structures. The PTD has become accepted as a major analysis tool for scattering calculations in that it can be easily implemented. Nevertheless, both PO and PTD are still approximate results and as such have potential errors. One error is associated with the current abruptly stopping at the shadow boundary on a curved surface. This error has been examined and found to be quite serious for

low observable targets. Thus, a general approach to solve such problems has been developed and published [2].

d. Low Frequency Scattering Code

Over the last few years the Electromagnetic Surface Patch (ESP) code has been delivered to and used by many engineers in industry, government and universities. These users had suggestions which were incorporated into the code. The number of changes became large enough that we felt that a revised version of the code and user's manual was warranted, and the revised code (ESP Version III) and user's manual [3] are now ready for distribution.

e. Bistatic Scattering from a Cone Frustum

Bistatic scattering has become of interest recently in that the scattering level is difficult to control for all bistatic angles. With this in mind, a research effort has been completed to study the bistatic scattering from conical shapes, the cone frustum being the target of interest as described in Reference [4].

f. External Scattering from Jet Intakes

The external scattering from the jet intake region for many missile geometries involves two major mechanisms; first, the direct scatter from the jet intake rim, and second the multiple scatter from the surface (using geometrical optics) to the rim. The ogive shape has again been used as a base and a circular jet intake rim has been mounted on the surface. Results show excellent agreement between measured and computed RCS for this case. This work is discussed in detail in a Ph.D.

dissertation by Volakis [5]. It is observed that many of these tools are also useful for the analysis of the scattering from externally mounted stores.

g. Reflection from Edge Like Structures

A study of the reflection from 2-D geometries that resemble wing profiles was undertaken since agreement between theory and experiment revealed that the theory generally predicted a value in the side lobe region that was low compared to measurement. This study was designed to evaluate the scattering as a function of frequency from the low frequency region where the leading edge could be represented as a half plane to higher frequencies where the reflection from the leading edge could be predicted via geometrical optics. This transition region study failed to give the expected increase in the scattered field, because the missing term was associated with the edge waves discussed in a previous section. A dissertation by Dominek [6] has been completed giving this and other results to be discussed in the next few paragraphs.

This study used as canonical targets: 1) circular cylinders, 2) parabolic cylinders, and 3) elliptical cylinders. The data for the first and last target (1 and 3) was corrupted by the presence of a creeping wave which had to be separated from the specular scatter via transient or time domain techniques. The second case (2) provided an exact solution for the specular scatter mechanism from the parabolic cylinder.

A model for the specular scatter was developed by Dominek that included not only the radius of curvature at the specular point but also

the distance to the shadow boundary. This model provides a reasonable means of treating the transition region mentioned above.

This thorough study has shown that the scattering from the leading edge of the wing profile was definitely <u>not</u> the source of the discrepancy between theory and experiment for complex targets. This has since been clearly demonstrated to be due to edge waves.

2. RCS Computer Codes

We proposed at the onset of this effort to develop a general purpose RCS computer code; however, the low observable security guidelines did not permit us to do so. Thus, we had to abandon this area until recently. The security guidelines have been modified during 1985 which allows us to develop such codes but not operate them for classified targets.

a. Aerodynamic/EM Interface

Careful examination of the various existing computer programs to represent body shape have been disappointing to a certain extent. The PANAIR program did not appear to be adequate, Rockwell's CDS system is company propietary and at one time we were approached by a Northrop Engineer who had suggested their computer program for target shape may be available; however, this did not occur. On the other hand, as stated earlier, NASA engineers had been examining their need and focusing their attention on the development of a suitable computer program to describe a general target shape. There were many discussions between NASA and OSU personnel to accurately pinpoint the needed parameters.

We have undertaken a joint effort with NASA (Langley, Virginia) to develop a general analysis for the scattering properties of complex aerodynamic shapes. Ray Barger [7] with the NASA aerodynamics group is basically putting the code together around their new aerodynamic geometry package. This geometry package is very significant in that it is designed to accommodate both the aerodynamic and electromagnetic features necessary for an accurate and efficient analysis. Our attention has been focused on the study of the limitation it may possess particularly in the region of forward scatter. This is essential when multiple scattering/diffraction occurs. This study has made use of an ogive although it is not restricted to this shape.

b. Flat Plate Scattering Code

In terms of shaping, it has been established that flat plate scattering is caused by various discontinuities such as an edge, corner, etc. If one curves the plate, some of the corners are now replaced by discontinuities in the radius of curvature. A study of these mechanisms is now complete. It makes use of the concepts of the UTD as applied to this new geometry. A dissertation on this topic by Chu [8] considers additional thin plate discontinuities and extends the analysis to treat the diffraction from a smooth junction formed by two curved edges with different radii of curvature. A general computer program has been developed and delivered to NASA for such plates. Chu also considers the smooth junction formed by surfaces of different radii of curvature and has also developed diffraction coefficients for this type of discontinuity.

c. Scattering Analysis and Codes

The scattering analyses/codes have been extended in two general ways. First, the electromagnetic scattering techniques discussed by Volakis have been made much more general by using the geometry codes developed by Barger of NASA. In a Master's thesis, Campbell [9] has evaluated the scattered fields from obstacles placed on surfaces described by Barger's geometry code.

A new technique, designated as an envelope analysis, has been developed that should prove very useful to aerodynamicists in that it allows them to quickly estimate the scattered fields from a shape under consideration. A thesis by Pistorius [10] has been completed showing a number of examples, and this effort is continuing.

d. Low Frequency Scattering Code

A moment method code has been developed by Newman [11] and delivered to NASA which treats general shapes that are not larger than ten square wavelengths. This code uses flat plate segments to simulate the structure. It is useful in treating objects whose overall length is not more than a few wavelengths. For a missile, it could be useful up to about 100 MHz; whereas for a fighter aircraft, it could be used to about 20 MHz. It has been verified by measurements taken in our compact range.

3. Indoor Scattering Measurement Systems

It was very apparent at the onset of this grant that state-of-the-art measurements were needed in order to verify our theoretical solutions as well as identify new mechanisms. As a result, various

indoor measurement facilities were evaluated to see their advantages and disadvantages. The compact range was most useful because it could handle large targets at high frequencies. Even though compact ranges were available in the early 1980's, they did not provide the performance needed for our sensitive measurements.

Nevertheless, our analysis showed that the various features limiting the compact range could be improved. Thus, a major effort with NASA to develop such systems was initiated. This required us to develop new feeds, reflectors, measurement hardware and target mounts. This, in conjunction with the improved compact range reflector, will make the facilities at NASA and OSU the best scattering ranges in the world. In this regard, we visited the major facilities in Great Britain a few years ago in order to evaluate our system versus theirs, and we can report that they had no comparable facilities.

a. Measurement Hardware

Originally, a standard CW nulling system was used for our measurements. This type of system is not very appropriate for compact range applications in that the horn-horn and horn-reflector-horn clutter terms are much larger than the target return. Two systems were proposed to solve this problem: 1) a pulsed/CW radar, and 2) a linear FM system. It was decided that OSU would evaluate the pulsed/CW system and NASA the linear FM one. As a result of our effort, a 6-18 GHz pulsed radar [12] was designed, constructed and evaluated. It very successfully eliminated the horn-horn and horn-reflector-horn clutter terms. In addition, it uses off-the-shelf components and is capable of measuring an 8 foot target.

More recently, our effort has concentrated on the development of pulsed/CW radar systems for compact range applications. Our 2-18 GHz system has been designed, constructed, and tested and found to be very reliable, efficient, and accurate. It is distinct from our previous system because the receive line switches have been moved from the RF side of the receive mixer to the IF side. This allows us to reduce the amount of RF hardware and still maintain excellent performance. Our sensitivity has improved by about 10 dB; in addition, our 5 ns wide receive pulse has allowed us to remove more room clutter which makes the system more stable. With our present room arrangement, our background after computer subtraction is about 70 dB below a square meter. With processing this can be improved by at least another 20 dB.

A prototype Ka-bandpulsed/CW radar using Ka-band components has been designed which is useful for frequencies between 30 and 35 GHz. After analyzing this system, it was found that it can be improved by using a minimum of Ka-band components [14]. Using this approach the transmit pulse is generated using our 2-18 transmit box which is then sent to a frequency doubler to generate the Ka-band signal. The receive signal goes directly to a mixer which converts the Ka-band return to an IF frequency. The receive switches are then added to the IF receive system. Using this approach one can measure an 8 foot target with better than a 60 dB below a square meter noise level.

b. Target Mounts

A complete low cross-section target pedestal was designed and built at OSU and delivered to NASA. In addition, a complete system controller

was developed, delivered, and evaluated at NASA by OSU personnel. This complete system is a duplicate of the one presently operating at OSU.

In order to measure conical patterns, a new target mount extension has been designed which will be attached directly to the target. It will be able to hold several hundred pounds and handle a hundred foot-pounds of torque at various elevation angles (0°, 10°, 20°, 30°, and 40°). Using this mount, NASA will be able to obtain conical patterns about the rotated axis.

The studies of absorber scattering have been useful in target mount designs. A target mount extension (designed at ESL) for the ogival pedestal, which directly attaches to the target, required treatment to reduce the mount scattering. A shroud was built to fulfill the need. The shroud consisted of commercially available layered absorber panel that was properly cut to form a wedge transition between the mount and free space.

Another mounting scheme has also been finalized. This entails the positioning and mounting of targets that require rigid metal mounts for stability. The mount concept is universal in the sense that the same hardware can be used for a variety of targets without having to have a unique mount for each target.

As shown by Lai [15], the metal ogive pedestal has too large a backscatter at lower frequencies. In addition, its bistatic scattering is not insignificant especially for scattering centers located off of the pedestal. To reduce the RCS of the pedestal, a treatment study was initiated; however to reduce the bistatic scattering, one must consider other mounting techniques such as straps hung from the chamber ceiling.

c. Compact Range Reflector Development

Most of our effort has been devoted to the improvement of the compact range facilities at both NASA and OSU. The OSU designed edges have been installed on the NASA reflector, and field probing has indicated that these edges are performing as desired. A second set of curved surfaces constructed by NASA have also been placed on OSU's reflector. The results of this effort have been reported in Reference [16]. Even greater benefits are to be obtained in the future in that a blended surface has been designed [17] that will make it practical to operate the compact range reflector at lower frequencies and for even larger targets.

These modified compact range reflector systems have attracted favorable nationwide attention from both government and industry. In particular, it has attracted the attention of several industrial organizations who are installing such a system as well as the manufacturer of the original reflector. For example, Scientific-Atlanta has redesigned their reflector and contributed a larger version of said reflector to OSU.

In order to properly feed the new blended surface reflector, a subreflector system has been designed for compact range applications [18,19]. In the process of designing this subreflector, it was found that one can correct the polarization problem associated with most off-set reflectors. This is done by tilting the subreflector axis relative to the main reflector axis. The tilt is rather small and in the off-set plane. This allows one to feed the main reflector properly to generate a uniform field in the target zone with excellent polarization purity.

The main reflector is still being designed in order to optimize its blended surface termination as well as the junction contour between the reflector and blended surface. It has been shown that this junction's diffracted field is dependent on the junction contour. Thus, an analysis to generate an optimum shape for this contour has been developed by Pistorius [19].

d. Simulation of Compact Range Reflector Systems

It has been our objective to examine the errors associated with the reflector system and correct them whenever possible. In terms of the reflector, the edge diffractions are the major source of ripple errors. So a major effort has been directed toward the reduction of these errors.

In order to accomplish this task, we have already developed a numerical technique to compute the diffraction from blended surfaces. The technique is based on the corrected PO solution [2]. Using this novel approach the total scattered fields in the near zone of the reflector are computed. One can then subtract the specular reflection term from the total scattered fields to obtain the diffracted fields. Using this numerical technique a computer code to analyze semi-circular compact range reflectors has been developed by Gupta and Burnside [20,21] and delivered to NASA (Langley). The code can be used to compute the total near field of the reflector or its individual components (specular reflection, aperture blockage scattered fields and feed spillover) at a given distance from the center of the paraboloid. The code computes the fields along a radial, horizontal, vertical or

axial cut at that distance. Thus, it is very effective in computing the size of the "sweet spot" for such reflectors.

The computer code, as mentioned above, can treat only semi-circular reflectors. The technique, however, is applicable to arbitrary edge paraboloid reflectors. For arbitrary edge reflectors, the technique becomes numerically inefficient in that computation time to carry out the PO integration becomes a limiting factor. Other methods to compute diffracted fields from the blended surfaces therefore need to be developed.

This code allows us to evaluate the presently-available Scientific-Atlanta reflectors and has shown that improvements are needed. Specifically, the edge contour of the parabola must be changed as shown by Pistorius [18], and the aperture blockage by the feed antenna reduced, the taper must be improved and the cross-polarization errors removed. As shown by analysis [19], these errors can all be reduced by using a dual chamber concept which utilizes a Gregorian subreflector located in a second small anechoic room. A small opening is then cut between the two chambers, so that the subreflector fields can fully illuminate the main reflector. This system is presently being constructed at NASA (Langley) and will be tested this coming summer.

e. Feed Designs

The blended surface design for the compact range reflector allows one to measure much larger targets. However, one can't take advantage of this target size unless he is able to feed the reflector properly. Heedy [22] has designed an aperture-matched horn which is useful for this application; however, it is larger than desired and not as

frequency agile as needed. As a result, other feed designs as well as subreflector approaches are being examined.

f. Absorber Scattering Study

A general study of absorber scattering has been initiated. This research effort involves both an analytic and measurement aspect in order to understand the scattering performance of commercially available pyramid and wedge absorbers. The analysis is based on a UTD corner diffraction solution which is modified to treat material structures. The major aspect of this analytic study is associated with the tip scattering. As this analysis was compared with measurements, it was ascertained that the absorber scatters incoherently; in which case, all the absorber contributes to the clutter throughout the room. Since the wall does not scatter coherently, one can't use a ray trace solution to design the anechoic chamber. Finally, the analysis and measurements by DeWitt [23] show that wedge material is clearly superior near grazing; whereas, the pyramidal material works better near broadside.

Based on the analysis of DeWitt [23], the absorber scattering properties are dictated by the homogeneity of the material. Attempts were made to get better material from absorber manufactures, but they don't seem to have the quality control necessary to improve the situation. They claim that their thin flat material is as homogeneous as they can possibly achieve with their present manufacturing techniques.

With this input, an absorber study was initiated to examine this flat material. They did appear to be more homogeneous, but flat material has too large a reflection coefficient. Thus, various layered

wedge absorber designs have been examined using this material. A 10 dB improvement has been achieved using this approach, but more refinement is needed.

g. OSU/ESL Compact Range Improvements

The anechoic chamber for the compact range has been drastically improved. The improvements entailed the refinishing of the reflector surface to provide a smooth rolled edge transition, a complete new absorber treatment of the walls, floors and ceiling, a raised floor to accommodate the ogival pedestal base and the installation of an overhead, remote controlled bridge crane to facilitate target mounting.

4. Control of RCS

The introduction of the traditional missile fins caused the scattered fields to increase substantially. Based on GTD scattering mechanisms and aerodynamic concepts supplied by C. Jackson of NASA, the fin shape was redesigned to lower its contribution to nearly that of the basic missile fuselage.

An oversized version was placed on the model, and the experiments verified our contention that a substantial reduction can be achieved by properly shaping the fins. This fin shape has been examined at NASA from an aerodynamic viewpoint and appears to have slightly better performance as compared with previous designs.

Based on experimental results, the major source of the scattered fields of the basic missile is from the rear of the fuselage. As a result, it was proposed that the rear be tilted to reduce this

contribution which could also be used to good advantage from an aerodynamic viewpoint as well.

The jet intake is another major source of scattered fields. For the present model, it is shielded by the missile body from the radar over a wide range of aspects looking from below the missile. The success of this shielding has been demonstrated by experiment. It has been proposed that this region could be extended by tilting the normal to the inlet upward from the axis of symmetry.

5. Waveform Processing Techniques

In the course of studying the reflection from the leading edge of a wing, the time domain techniques have been further developed by Dominek [24]. These techniques generally required accumulation of data over a wide range of frequencies. This data is then transformed to the time domain, producing a series of scattered waveforms from each scattering mechanism. Unfortunately, when the portion of the spectrum of interest is that where the dimensions of the body are small in terms of wavelength, these transient signals tend to overlap. Thus various types of windowing were introduced to obtain the desired separation. These techniques have proven useful in the evaluation and control of scattered fields.

This study has also produced some additional results for creeping waves. The importance of creeping waves arises in low level radar cross section (RCS) bodies since they can be scattered back by structures shadowed by the main body. A smooth, elongated missile-like body was made with several removable inlets to investigate, by measurement, the influence of a shadowed inlet in regions of low RCS. The measurements

indicated a definite low level creeping wave interaction with the inlets. However, the level was near our lower measuring capability limit. This limit is being substantially reduced at the present time for future measurements. At the same time, a computer code was developed to calculate these creeping wave interactions based on GTD [25] and incorporating numerical techniques developed at NASA [7]. The accuracy of these calculations is dependent upon how well the GTD creeping wave formulation models surface diffraction mechanisms. It is well known that the formulation is very accurate for circular and spherical surfaces but very little study has been done on elongated surfaces. There has been an effort to compare the GTD creeping wave formulation to the true creeping wave values for spheroids and ellipsoids by extracting the creeping portion from the total scattered field of these two surfaces. There is as yet no valid asymptotic solution for low frequencies in terms of the creeping wave format for elongated bodies; i.e., pariaxial diffraction occurs.

It is desired to remeasure the shadowed inlet RCS contribution in the improved anechoic chamber to have very reliable measurements and to finish the creeping wave comparison to establish the accuracy of the GTD formulation for elongated surfaces.

The time domain extraction technique discussed earlier is one of many possible techniques to obtain the frequency characteristics (RCS) of a particular scattering mechanism by a "filtering" process from the total scattered field of a body. Other filtering techniques are also possible such as one developed by Ksienski [26]. Ksienski's approach has been generalized and is actually similar to filtering techniques used in time series analysis and geophysical seismograph research. The

literature has been reviewed in those other areas to find other applicable filter techniques that could prove useful in scattering problems.

Another area where time series analysis and geophysical seismograph research can provide useful results is in high resolution time domain techniques. The time domain resolution capability of scattering centers is proportional to the frequency bandwidth. These other disciplines have generated techniques to "sharpen" the scattering center response that simulates the effect of having more bandwidth.

The general direction of this area of research is to improve the resolution and quality of data obtained using various processing techniques. These studies have been directly applied to a number of real world situations and have shown some successes. This whole effort will continue in an attempt to develop new and more powerful tools to extract more information from measured data.

As a result of our studies, a new cross-range measurement algorithm has been developed for specific application to the compact range. Using this approach, the target is examined at a few look angles in one plane by simply moving the feed antenna. Since each feed position can be calibrated, the down range image plots from each look angle can be combined to create a cross-range scattering center location. More will be presented on this topic in the future.

6. Material Study

The use of materials has proven to be quite rewarding. Both anisotropic composite materials and absorbers have been used to eliminate the edge wave that is generated at a discontinuity such as

corner, propagates along an edge and diffracts from a second discontinuity. This has proven to be a very significant scattering mechanism for both aircraft and missiles, particularly the supersonic vehicles with their sharp edges. This mechanism must be eliminated if the current analysis (and treatment) of leading and trailing edges is to be valid. A report has been written describing this result [27].

The rim for jet intakes has been shown to be a primary scattering source. Means of controlling this rim via the anisotropic material approach has been considered. A series of measurements have been made for open ended cylinders composed of such materials to obtain a basic data base. The results of these measurements have been interpreted. The use of these materials has proven to be a diagnostic tool in that diffraction/scattering from a given portion of a structure can be modified by its presence.

A report [28] has been issued summarizing the use of composite materials. A second report [29] associated with nearly flat structures or straight edges has also been written. Our work with W.T. Hodges in this area has proven to be very rewarding in that we have gained a much better physical insight into the structural features of composites. Work has been focussed on structures that are self supporting and will achieve the desired electromagnetics performance.

7. Design and Evaluation of Standard Targets

A number of standard targets have been developed, constructed and tested by NASA and OSU. One, an "almond" shape [30], is a very low echo area object and has been used to study perturbations including small intakes. This same scatterer is of interest to DoD and industry as a

test shape. The second test body called the "peanut", was used to study multiple scattering. A third structure, the generic inlet has been compared very favorably with computations using a hybrid solution.

Canonical shaped bodies like the ogive and sphere-capped cylinder have been pursued as targets to evaluate a measurement facility. An effort is presently underway to efficiently generate the calculated scattered field from these bodies when they are electrically large to obtain an absolute reference of what a range should measure.

The "almond" has proven to be a very desirable support body in terms of its scattering characteristics. The almond allows a very large angular sector where the scattered field is very low. This feature allows the direct measurement of a subcomponent on the surface of the body without having the measurement corrupted by scattering arising from the support body. The almond can also be rigidly supported on the low cross section ogival pedestal for measurements.

The evaluation of the almond test body has progressed to the point of routine use for subcomponent measurements. The almond version most commonly used is the 'flat' one which on side has a planar surface to facilitate subcomponent mounting. A flush, removable ogival plate which covers a cavity region has been incorporated on this flat portion.

The calculation of the scattering from an almond body is presently underway using a "March-in-Time" approach of Bennett's [31]. This calculation is being performed on a Cray computer located at Carnegie-Mellon University. Such calculations are useful for performance checks on measured results from anechoic chambers.

8. Aircraft Blockage of Ground-Satellite Link

The potential for an aircraft to fly directly through a ground station-to-satellite link becomes more significant if the link is located closer to an airport, obviously. Because this situation is much more likely near airports, it is appropriate to examine the effects of such an encounter.

There were two aspects to this study: 1) an aperture blockage theoretical solution developed by Rudduck and Lee [32] was used to calculate the effect of a large aircraft (C5) for various satellite ground station antenna diameters, and 2) the compact range facility at OSU was used to measure the blockage of various targets, including a 737 aircraft, and to validate the theoretical solution of Item 1.

The measurements verified the theoretical analysis in that the blockage results from the obstruction of the line-of-sight signal. In all cases if a large aircraft flew directly through a ground station-satellite link, there can be a drop in the system gain. What effect this has on the system is dependent on the system under consideration. However, as shown in Ref. [33,34], if the aircraft is in the near field of the ground station, the gain loss is substantial, and one would assume that the link would be lost during the time period that the aircraft blocks the line-of-sight signal.

9. Inlet Internal Scattering Analysis

A hybrid technique was used to analyze the general rectangular inlet structure. The agreement of this solution's results with experimental ones was excellent. In addition, it was studied further to determine how much of the complexity of the internal fields needs to be

retained in order to obtain good results. It was surprising to learn that only three waveguide modes dictated by the angle of incidence were required to generate accurate results even when the rectangular cross section is relatively large in terms of the wavelength. Furthermore, this hybrid technique, which involves a combination of high frequency (HF), modal and multiple scattering methods, has been developed to deal with a variety of inlet shapes which can be approximated by joining together piecewise linearly tapered and/or circularly bent sections of waveguides for which the modes can be determined. This hybrid technique basically involves expressing the modes in terms of an equivalent set of modal rays and then finding the elements of the junction scattering matrices in a relatively simple manner, via HF techniques, to characterize the junction discontinuities. The interactions between junctions (discontinuities) is accounted for by the self consistent multiple scattering method to arrive at the total field scattered by the inlet model. This work is summarized in Ref. [35,36].

A second much simpler ray optics model was also studied by Burkholder [37]. It was found that good results are obtainable even from this simple geometry. This is especially true for internal structures that are very large electrically.

In both cases, the analytic results were compared with measured results obtained using the compact range system. The inlet models were supplied by NASA.

An efficient hybrid procedure was developed, as mentioned earlier, for analyzing the electromagnetic scattering by a class of inlet shapes that can be modeled by joining together piecewise, linearly tapered, and/or circularly bent sections of waveguides for which the modes can be

found analytically. This hybrid procedure begins by breaking up the modal fields in terms of an equivalent set of modal rays, and then using these modal rays in conjunction with asymptotic high frequency techniques (such as the geometrical and physical theories of diffractions) to find the elements of the generalized junction scattering matrices in a relatively simple form. These scattering matrices fully characterize the reflection and transmission properties of the junctions between different waveguide sections. The interaction between different waveguide sections (discontinuities) is readily accounted for by the self consistent multiple scattering method. When applying this approach to a general rectangular inlet cavity, it was also mentioned previously, that, a further simplification was achieved because only a set of three consecutive waveguide modes dictated by the angle of incidence were needed to get accurate estimates of the RCS for sufficiently large waveguides. During the present period, that selective modal scheme has been studied for other inlet waveguide shapes such as strongly linearly tapered as well as circular inlets. While it is found that more selective modes are required for the latter configurations than for the rectangular case analyzed previously, it is true that the selective modes still form a far smaller set than the large number of all the propagating modes within the inlet waveguide. The work on the hybrid approach for analyzing the junction scattering matrics and the evaluation of the RCS of some inlets, as well as the selective modal scheme are described in a report and few papers which are listed later in the section on recent publications.

Before proceeding to analyze the RCS of more inlet shapes, it appears appropriate at this time to consider alternative efficient

approaches for analyzing inlets with smooth transitions and tapers which could also account for inlet wall treatments. Such a study of this complex problem is under way. The hybrid modal ray approach discussed earlier will become more difficult and cumbersome for arbitrarily shaped inlets and for treated inlet walls, as the modes are very difficult to find for the latter case. Nevertheless, the studies performed thus far on a class of perfectly-conducting inlet models (for which the interior modes can be found easily) provide a useful estimate of the upper bound for the inlet RCS values; the treated inlets would of course yield mostly lower RCS values.

10. Antenna Studies

a. Array Scan Impedance

The study of scattering by antenna arrays is continuing. The general property of the array that needs to be evaluated and controlled is the array scan impedance. It is very important that this scan impedance be made as independent of scan angle as possible. To this end our original studies involved techniques for controlling the impedance of an array of "V" dipoles over a conducting plane. A reasonably constant scan impedance has been obtained for such an array. However, when the feed lines were inserted, these desirable results were seriously perturbed.

b. Microstrip Scattering

In this section the current and future work on the method of moments (MM) analysis of the radiation and scattering from microstrip antennas and arrays is described. A microstrip antenna is a metal patch

printed on an electrically thin grounded dielectric substrate. The main purpose of our effort is to develop an accurate and computationally efficient model for the radar cross section (RCS) of a rectangular microstrip antenna over a very broad frequency range. The RCS of the microstrip antenna is an important problem since its scattering can be dominant when mounted on a low RCS structure.

Our past work [38-43] (and that of others) on microstrip antennas has mostly dealt with the radiation problem. In this case, we were interested in the transmitting properties over a frequency range within a few percent of first resonance. We are now interested in the scattering properties over a frequency range of several octaves. A result of this is that the current distribution on the microstrip patch is very complicated, as compared to the relatively simple current distribution on a transmitting microstrip near the first resonance. Thus, we must use many terms, N, in our MM expansion of the microstrip current. This presents a problem, since the CPU normally increases as N^2 in a MM solution.

We have done two main things to obtain an efficient MM solution with reasonable CPU times. First, we have formulated the solution so that the reasonable CPU time is proportional to N rather than N^2. This minimizes the CPU time to compute the RCS at a single frequency; however, a second problem remains. The microstrip antenna is a highly resonant device. A plot of RCS versus frequency would consist of a series of large, but narrow peaks. In order not to miss one of these peaks, we must take small steps in frequency. Consider the computation of the RCS of a microstrip antenna from 1 to 10 GHz. If we take frequency steps of say 10 MHz, then this would result in 1000

evaluations of the MM computations, and the total CPU time would be prohibitive. To alleviate this problem we have developed a technique of interpolating the MM impedance matrix. In the above example, we might compute the MM impedance matrix every 500 MHz, resulting in a factor of 50 decrease in CPU time. The impedance matrix at an intermediate frequency works because the elements in the impedance matrix are a much more slowly varying function of frequency than the scattered field.

At present, we have developed a computer code capable of computing the RCS of a rectangular microstrip patch over a broad frequency range. We have also obtained measurements to verify the accuracy of the code. All of which was reported in Ref. [44].

The present code does not consider the microstrip feed. For the antenna problem, one can use an extremely simple model for the feed, which assumes an extremely thin substrate. However, for the RCS problem we can not assume a thin substrate, since the frequency of the incident wave might be much greater than the frequency of the first resonance of the patch. Thus, our efforts have been directed toward developing a suitable model for a microstrip feed. This model will enforce continuity of current at the feed line to microstrip patch junction, and not be dependent on a thin substrate approximation. Basically, this will be done by taking our past work on wire to plate junctions [45-48] and modifying it for the microstrip antenna.

11. Miscellaneous Measurements

a. Rough Surface

A variety of measurements have been performed during this past year. One centers around the scattering from rough surfaces near

grazing. Measurements of a plate with periodic sinusoidal variations were obtained and compared with simple theory. The peak to peak surface variations were .01 and .03 inches. The resonant behaviours of the scattered fields were readily apparent and agreed with the calculations for incident angles less than 30° from grazing.

b. Resistive Cards

Another series of measurements involve effectiveness of resistive cards on thick edges. Resistive cards are very useful for scattering reduction from thin edges but when the edge becomes thicker, the scattering phenomenon changes. The scattering reduction from an elliptic edge was measured over a broad band of frequencies at several look angles for single and multiple resistive card configurations.

c. Contour Rim Inlets

The scattering reduction possible on shaping the rim of inlets was experimentally studied. Four different rim contours were tested: a straight circular rim, an outwardly expanding rim, an inwardly contracting rim and a rim contour that oscillated about a plane. It was found that no significant difference was observed among a series of pattern and swept frequency measurements. Conceptually, an oscillating rim would reduce the axial backscattered field if enough phase difference could be achieved.

d. Images

A new scheme to generate two-dimensional images of scattering centers has been developed. This technique entails the processing of

downrange, bandlimited impulse responses from two look angles which are symmetrically offset a slight distance from the downrange symmetry axis of the compact range reflector. The returns from the two look angles are paired together and the downrange location of the scattering centers is the average downrange distance of each pair. The crossrange displacement of the scattering center is obtained from the relative downrange offset between the average downrange location and the individual returns. To determine whether the scattering center is located to the left or right of the down range symmetry axis, the measurement which precedes the average downrange location is used. This algorithm is well suited for reflection and diffraction mechanisms.

C. PRESENT PROGRAM ACHIEVEMENTS

1. Indoor Scattering Measurement System

a. Compact Range Reflector Development

For the past several years, we have been working jointly with NASA (Langley) to develop the next generation reflector system which will provide at least an order of magnitude improvement in the system performance. The concept as stated earlier involves a Gregorian subreflector system built into a dual chamber arrangement. Using this approach, we expect to obtain about 1/10th dB ripple and taper errors. Plus, the cross polarized component should be at least 40 dB below the co-polarized term. This system should be constructed and tested this coming summer.

It was shown by Pistorius [19] that a concave edge contour reflector provides better performance because it reduces the spread factor or ultimately the diffracted field. In order to simply test that

concept, he used the same blended rolled edge around the entire reflector contour. His results showed some improvement; however, the reflector rolled edge was not optimized. As a result, we have been developing an optimization concept for the blended rolled edge for each section around the concave edge contour. This is done by optimizing the blended rolled edge along selected radial cuts around the reflector. The blended rolled edge at each radial cut is then found by interpolating the blended rolled edge parameters from one optimized section to the next. The optimization is done by first finding the equivalent parabola for each selected radial cut through the center of the reflector. Using this equivalent parabola, we obtain an optimized rolled edge based on the lower frequency and height requirements. This approach provides even better performance than that obtained earlier.

Last year, we developed an improved Physical Optics (PO) solution for the rolled edge reflectors which required us to subtract out a shadow boundary error term as described in Ref. [2]. This error mechanism consists of several terms but for most cases can be limited to the first and second order terms. The second order term requires us to know the radius of curvature of the curved surface at the shadow boundary. This radius of curvature is not that simple to obtain but must be evaluated in order to obtain accurate results. We have recently evaluated this radius of curvature and found that the second order term has a significant effect on the results. In fact, the removal of this error term from the PO solution allows us to generate even better reflector designs such as the optimized shape described previously.

b. Measurement Hardware

The majority of our effort this year has been devoted to the development of two pulsed/CW radar transceiver systems for NASA (Langley). These systems are based on a prototype design which was also designed, constructed and tested this year. The transceiver is operational from 2-18 GHz with additional capability from 18-36 GHz using a few higher frequency components. This is done using a double concept which sacrifices some performance because of the lower radiated power (+5 dBm versus 20 dBm).

The radiated signal is pulsed with a width of about 5 ns to eliminate clutter mainly associated with the horn VSWR and bounce off the reflector. The pulses can be controlled to a resolution of 1 ns in terms of their delay and width. These signals are fully controlled by the IBM/AT computer which is interfaced to the system.

The receiver subassembly consists of two independent channels which can be used to measure the co-polarized and cross-polarized signals scattered by the target. These two signals are coherently detected to a resolution of 0.001 dB and 0.01°. In order to provide various performance parameters, the system can be requested to hardware average the detected signal from 1 to 256 samples. Thus, the operator through the IBM/AT controller can tradeoff system performance for speed.

In that one would like to eliminate the need for taking numerous background measurements, the system must remain very stable with time. This stability is built into the radar by shifting the receive pulse gate between a fixed or known return and the target. The target return is then divided by the known one in order to remove the system

variations. This reference mode can be selected or not by the operator for each new measurement.

The software on the IBM/AT computer is menu driven under cursor control to allow the operator to view the receiver settings and simply change only selected parameters. It is divided into several pages which perform different functions such as target log and scan parameters page, measurement page, processing page, timing page and maintenance page. Through this input one can easily specify a measurement sequence and obtain the desired data. On the other hand, if the system is perceived to have a problem, it can be self evaluated to check out each subassembly. If a problem is indicated, the operator can further examine the system using the maintenance page. Once the faulty section is defined, it can be removed and tested on the bench.

This new system has been tested thoroughly and been found to perform up to its original design specifications. The first system will be delivered to NASA (Langley) in May; whereas, the second one will remain at OSU in order to interface it with the new mini range reflector system.

c. **Target Mounts**

In order to make the NASA (Langley) radar system compatible with ours, we have also modified our old metal ogival support pedestal and added a new pedestal controller. This will make the new radar system completely stand alone except it must be interfaced to the NASA MicroVax computer. All the software and hardware for this interface has already been delivered to NASA.

We have made some great progress using straps to hold a target. This work has not been done under this grant, but it should be kept in mind as a potential future method for holding targets during a measurement sequence. We have found that the specially designed straps from 3M Corporation can hold very heavy targets; yet, their cross-section at a small tilt angle relative to the plane wave direction can be better than -60 dBsm. In addition, their bistatic scattering level is very low so that they don't interact significantly with the target except for the mounting fixture. As a result, we will need to evaluate various strap mounting techniques in the future.

d. Absorber Scattering Study

This effort has been devoted to the absorber treatment of the aperture opening between the two chambers in the Gregorian subreflector system. This has involved evaluating various absorber treatments in the aperture and recording the resulting antenna patterns. The actual measurements have been obtained at NASA (Langley). The absorber performance has been critically examined using a new cross range algorithm which identifies the various scattering (or radiation) centers associated with a sector of the measured pattern. Using this approach, we have been able to pin-point the significant scattering regions and modify those areas to improve performance. Without such a technique, it would be virtually impossible to determine which portion of the total absorber treatment caused a 1/10th of a dB ripple. At the present time, these techniques have just about specified the absorber treatment for the aperture opening for x-band operation.

e. Cross Range Processing for Antenna Patterns

As stated in the previous section, we have developed a new algorithm to identify the cross range location of the radiation centers based on a small sector of the radiation pattern. This is done by coherently processing the pattern data for say plus and minus five degrees around a pattern direction of interest. If it can be assumed that the magnitude of a radiation center is uniform across this small angle scan the phase indicates the various sources of the radiated signal.

This processing has been used to evaluate the radiating centers for an 8 foot diameter reflector antenna which was measured in our compact range. Simply using the recorded patterns, we could identify the feed spillover, feed blockage, edge diffraction and strut scattered field locations and relative radiation levels. In addition, we obtained other terms which were unexpected such as scattering from a small taped hole in the center of the reflector. This error term was large enough to destroy the agreement between measured and calculated results because the calculated data didn't include that term. In any event, it is very clear that this type of signal processing will become more popular in the years to come. In that regard, the compact range is most appropriate for this technique in that it can provide the required measured phase accuracy as demonstrated by our results.

f. Recent Indoor Scattering Measurement Publications

1. V.D. Burnside, "Compact Ranges - Past, Present and Future," IEEE Antennas and Propagation Society International Symposium, Blacksburg, VA, June, 1987.

The compact range has been used for electromagnetic measurements since the early 1950's. Although the early attempts with such systems had some successes, they were not generally used until the middle of the 1970's. This recent interest was sparked by a commercially available system developed by Scientific-Atlanta. This system was specifically designed and tested for antenna applications even though the earlier tests were made in terms of scattering measurements. Based on the recent interest in radar cross-section, the compact range has been re-examined in terms of its capabilities for measuring the scattering properties of large structures. The Ohio State University has been one of the pioneers in developing the proper use, capabilities, and modifications necessary to make the compact range one of the most accurate electromagnetic pattern measurement systems available. As a result, new systems have been designed using various electromagnetic analyses to guide this research effort. These changes include the reflector, feeds, target mount, instrumentation, absorber, target handling techniques, data processing, calibration methods, calibration targets, etc. In most cases, the theoretical solutions have been verified by experimental results, and in some cases, the new designs have been incorporated in commercial products.

The presentation will attempt to cover the latest and more interesting aspects of this challenging new area.

2. I.J. Gupta and V.D. Burnside, "A Numerical Method to Compute Diffraction from Blended Surfaces," IEEE Antennas and Propagation Society International Symposium, Blacksburg, VA, June, 1987.

The compact range reflectors used for RCS and antenna measurement these days usually have rolled edges [1,2] to reduce the stray fields diffracted from the rim of the parabolic section. For the optimum performance (small diffracted fields), blended rolled edges [2] are used. The junction between the parabolic section and a blended rolled edge is a higher order discontinuity in that at least the radius of curvature at the junction is continuous. Closed form solutions for the fields diffracted from such junctions are not available. Thus, it is quite hard to analyze and design such compact range reflectors. In this paper, a numerical method to compute fields diffracted from blended surfaces is presented. The method is applicable to reflectors with arbitrarily shaped rims and is specially

suitable for circular or semi-circular reflectors. A brief description of the method is given below.

3. C.W.I. Pistorius, G. Clerici and W.D. Burnside, "A Dual Chamber Compact Range Configuration," IEEE Antennas and Propagation Society International Symposium, Blacksburg, VA, June, 1987.

A compact range is an indoor facility used for the measurement of antenna radiation and target scattering patterns. The measurement of these patterns require that the antenna or scattering body be illuminated by a uniform plane wave; i.e., the measurement range has to be able to produce a uniform plane wave with no cross-polarization errors (or a good approximation thereof) over a specified volume where the target or antenna will be located, referred to as the "target zone". It has already been shown that edge diffracted fields from the main reflector can be significantly reduced if the main reflector has a concave edge contour and blended rolled edge terminations [1,2]. This results in a reduction of the ripple in the field illuminating the target zone. In this paper, it will be shown that the range performance can be improved further by using a dual chamber compact range configuration [3] as shown in Figure 1. The main reflector and target zone are located in the main chamber and a Gregorian subreflector and associated feed assembly in a second, smaller chamber. The two chambers are separated by an absorber fence, with a small coupling aperture to transmit signals from one chamber to the other. Since all the reflected rays from the Gregorian subreflector pass through the focal point, and hence through the coupling aperture, they are not perturbed by the absorber fence. Such a dual chamber system has several advantages over other configurations, especially in terms of a reduction of the amplitude taper and cross-polarization errors in the plane wave illuminating the target zone.

4. I.J. Gupta, W.D. Burnside and C.W.I. Pistorius, "Design of Blended Rolled Edge for Compact Range Reflectors," AMTA Symposium Digest, Seattle, WA, September, 1987.

The compact range reflector used these days for RCS and antenna measurements have rolled edges [1] to reduce the stray fields diffracted from the rim of the parabolic section. For optimum performance (small edge diffracted fields), blended rolled edges [2] are used. A blended rolled edge ensures that the radius of curvature of the surface is continuous at the junction between the paraboloid and the rolled edge. By selecting an appropriate blending function, one can make the first and higher derivatives of the radius of curvature continuous at the junction [3] which in turn results in a weaker diffracted field. However, the resulting

reflector may be too large to be practical. Also, the minimum radius of curvature of the reflector surface in the lit region may become less than one fourth of the wavelength at the lowest operating frequency, which is not desirable. Thus, the choice of blending function and rolled edge parameters is quite important in the design of compact range reflector antennas. In this paper, a procedure to design blended rolled edges for such applications is discussed. The design procedure leads to a rolled edge that minimizes the edge diffracted fields while satisfying certain constraints regarding the reflector size and minimum operating frequency of the system. Some design examples are included.

5. H. Shamansky, A. Dominek and W.D. Burnside, "Remodeling of the ESL-OSU Anechoic Chamber," AMTA Symposium Digest, Seattle, WA, September, 1987.

The indoor compact range has proven to be quite successful in measuring the radar cross section (RCS) of various targets. As the performance capabilities of the compact range have expanded, the use of larger, heavier, and more sophisticated targets has also expanded. Early target dimensions were limited by the size of the useful test area, as well as the capacities of the low RCS pedestal mount used. Today, our anechoic chamber has a large useful test area, thus the size and weight of targets dictate that a new method be employed in target handling and positioning, as well as target mounting to a low RCS pedestal.

Work was recently completed here at the Ohio State University ElectroScience Laboratory to remodel our anechoic chamber to allow for the new generation of targets and the demands that they place on the anechoic chamber. This work includes the addition of a one ton motorized underhung bridge crane to our anechoic chamber, the design and construction of an hydraulic assist to smoothly and precisely raise and lower the target for the final link-up of the support column and the receiving hole in the target, the design and installation of a one ton telescopic crane in the chamber annex to link with the main chamber crane, the design and installation of the necessary microwave treatments to minimize the impact of the remodeling on accurate RCS measurements, the development and installation of a sloping raised floor, the design and manufacture of a track guided rolling cart to shuttle operating personnel to and from the target area, the replacement of the existing radar absorbing material, the improvement of the ambient lighting in the chamber to facilitate film and video tape documentation, and the development of new target mounting schemes to ensure ease of handling as well as secure mounting for vector background subtraction.

6. W.D. Burnside, C.W. Pistorius and M.C. Gilreath, "A Dual Chamber Gregorian Subreflector of Compact Range Applications," AMTA Symposium Digest, Seattle, WA, September, 1987.

A new dual chamber concept using a Gregorian subreflector system is being proposed for compact range applications. This concept places the feed and subreflector in a small chamber adjacent to the measurement range which contains the main reflector and target. These two chambers are connected together by a small aperture opening which is located at the focus of the main reflector. This system can potentially provide improved taper, ripple, and polarization performance. Because it sues a refelctor, the amain reflector focal length can be decreased without a loss in performance. This in turn reduces the minimum length requirement for the main chamber. The design of this type of system plus the test results that have been performed will be presented at the conference.

7. B.J.E. Taute, W.D. Burnside, and I.J. Gupta, "The Effects of Mechanical Discontinuities on the Performance of Compact Range Reflectors," AMTA Symposium Digest, Seattle, WA, September, 1987.

Reducing ripple in the aperture field of the parabolic reflector is one of the main considerations in the design of a compact range, since it determines the "usable" target zone for RCS and antenna measurements. The usable target zone is typically defined as the aperture region where the ripple is less than 0.1 dB [1]. Studies [2,3] have shown that edge diffractions and therefore ripple can be significantly reduced by using blended rolled edges such as in Figure 1. For low aperture field ripple, it is assumed that the junction between the parabolic surface and the blended rolled edge is smooth. In practice, however, the rolled edges may be machined separately and then fitted to the main reflector. If this is done, small wedge angle errors (Figure 2) or step discontinuities (Figure 3) may be mechanically introduced at the junctions. Typically, angle deviations of $\pm 0.5°$ and steps of ± 0.005 inches may be expected. If the parabola and part of the rolled edge is machined as a unit, diffractions due to discontinuities in the mechanical junction between this surface and the rest of the rolled edge can have less effect on ripple in the aperture field. Now, the questions to be answered are:

- How much of the target zone is lost due to discontinuities at the edge of the parabola?
- How much of the rolled edge need to be machined with the parabola to prevent mechanical discontinuities from decreasing the usable target zone?
- What range of discontinuities can be tolerated?

In this paper, these questions are answered for a 12-foot radius semi-circular compact range reflector with cosine-blended rolled edges.

8. C.W.I. Pistorius, "New Main Reflector, Subreflector and Dual Chamber Concepts for Compact Range Applications," Technical Report 716148-22, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, August 1987.

A compact range is a facility used for the measurement of antenna radiation and target scattering problems. Most presently available parabolic reflectors do not produce ideal uniform plane waves in the target zone. Design improvements are suggested to reduce the amplitude taper, ripple and cross polarization errors. The ripple caused by diffractions from the refelctor edges can be reduced by adding blended rolled edges and shaping the edge contour. Since the reflected field continues smoothly from the parabola onto the rolled surface, rather than being abruptly terminated, the discontinuity in the reflected field is reduced which results in weaker diffracted fields. This is done by blending the rolled edges from the parabola into an ellipse. An algorithm which enables one to design optimum blended rolled edges was developed that is based on an analysis of the continuity of the surface radius of curvature and its derivatives across the junction. Furthermore, a concave edge contour results in a divergent diffracted ray pattern and hence less stray energy in the target zone. Design equations for three-dimensional reflectors are given. Various examples were analyzed using a new physical optics method which eliminates the effects of the false scattering centers on the incident shadow boundaries. A Gregorian subreflector system, in which both the subreflector and feed axes are tilted, results in a substantial reduction in the amplitude taper and cross-polarization errors. A dual chamber configuration is proposed to eliminate the effects of diffraction from the subreflector and spillover from the feed. The main reflector and target zone are located in the upper chamber, and the subreflector and feed in the lower chamber. the chambers are isolated by an absorber fence with a small coupling aperture to transmit signals. The fence attenuates stray signals from the subreflector and feed to an insignificant level. Diffraction from the coupling aperture can be minimized by terminating the fence in wedges. A computationally efficient technique, based on ray tracing and aperture integration, was developed to analyze the scattering from a lossy dielectric slab with a wedge termination.

9. H.T. Shamansky, A.K. Dominek and W.D. Burnside, "Design and Implementation of the ESL Compact Range Underhung

Bridge Crane," Report No. 716148-23, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, September 1987.

As the indoor compact range technology has continued to increase, the need to handle larger and heavier targets has also increased. This need for target lifting and handling prompted the feasibility study of the use of an under hung bridge crane to be installed in the ESL compact range. This report documents both the design of the underhung bridge crane that was installed and the implementation of the design in the actual installation of the crane.

10. T.H. Lee, W.D. Burnside and R.C. Rudduck, "A New Approach for Shaping of Dual-Reflector Antennas," Report No. 716148-26, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, December 1987.

A new approach is studied for the shaping of two-dimensional dual-reflector antenna systems to generate a prescribed distribution with uniform phase at the aperture of the second reflector. This method is based on the geometrical nature of Cassegrain and Gregorian dual-reflector antennas. The method of synthesis satisfies the principles of geometrical optics which are the foundations of dual-reflector designs. Instead of setting up differential equations or heuristically designing the subreflector, a set of algebraic equations are formulated and solved numerically to obtain the desired surfaces. The caustics of the reflected rays from the subreflector can be obtained and examined. Several examples of two-dimensional dual-reflector shaping are shown to validate this study. Geometrical optics and physical optics are used to calculate the scattered fields from the reflectors.

A blended rolled edge attachment to the shaped main reflector for compact range applications is also investigated. The addition of rolled edges to the main reflector reduces the edge diffracted field which causes ripple in the aperture field. A method for correcting false end-point contributions which result from the use of physical optics are reviewed. Several examples are given to illustrate the improvement achieved in the aperture field by adding the blended rolled edge terminations. Corrections for the end-point contributions are included in these examples in order to obtain the true scattered fields from the reflectors. The same method of synthesis is also used for shaping of a three-dimensional circularly symmetric dual-reflector antenna. This case is also verified by examples.

11. D. Jones, B.W. Burnside, "A Very Wide Frequency Band Pulsed/IF Radar System," Report 716148-28, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, March 1988.

A pulsed/IF radar for compact range cross section measurements has been developed which converts RF returns to a fixed IF, so that amplification and gating may be performed at one frequency. This permits the use of components which have optimal performance at this frequency which results in a corresponding improvement in performance. Sensitivity and dynamic range are calculated for this system and compared with our old radar, and the effect of pulse width on clutter level is also studied. Sensitivity and accuracy tests are included to verify the performance of the radar.

12. S. Ellingson, "Curvature of Blended Rolled Edge Reflectors at the Shadow Boundary Contour," Report No. 716148-29, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, April 1988.

A technique is given to compute the radius of curvature of blended rolled edge reflector surfaces at the shadow boundary, in the plane perpendicular to the shadow boundary contour. This curvature must be known in order to compute the spurious endpoint contributions in the physical optics (PO) solution for the scattering from reflectors with rolled edges. The technique is applicable to reflectors with radially-defined rim-shapes and rolled edge terminations. The radius of curvature for several basic reflector systems is computed, and it is shown that this curvature an vary greatly along the shadow boundary contour. Finally, the total PO field in the target zone of a sample compact range system is computed and corrected using the shadow boundary radius of curvature, obtained using the technique. It is shown that the fields obtained are a better approximation to the true scattered fields.

2. Material Study

Research on new mechanically strong surfaces with reduced edge waves has continued. This structure has been used in the design and development of more practical structures. An ogival shape whose construction is nearly complete should provide some interesting results during the current contact. Even more interesting have been results

generated by structures that are more closely related to actual aircraft shapes. A preliminary report has been written discussing these advances.

The analytic study of these surfaces has provided an improved understanding of these materials. Thus, it is most important that these studies continue. These results suggest that optimum absorption of surface waves occurs when fiber radii are of the order of a skin depth. If further studies confirm this concept, and we succeed in adequately matching measured and computed results, this will result in substantially improved composites from an electromagnetic view point. A report has been written describing these studies.

In addition, the material contained in Reference [28] is to be included in the recent low observables symposium digest.

a. Recent Publications

1. T. Hodges, (NASA/Langley Research Center, Hampton, VA), E. Newman, L. Peters, Jr., (OSU-ElectroScience Laboratory, Cols., OH), "Preliminary Version of an Electromagnetic Model for Graphite Composites", Report No. 716148-25, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, November 1987.

"Classified"

2. A.K. Dominek, L. Peters, Jr., "Edge Wave Control on Three-Dimensional Fins", Report No. 716148-27, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, September 1987.

"Classified"

3. L. Peters, Jr., A.K. Dominek, S. Wozniak, R. Swann and W.T. Hodges, "Edge Wave Control Using Absorber on

Composite Material," Low Observables Symposium Digest, March 1988.

"Classified"

3. Waveform Processing Techniques

In our effort to develop new and more powerful tools to extract more information from measured data, we are studying various super resolution techniques used in spectral estimation. These techniques offer superior resolution with the added benefit that far fewer data points are needed in the measurement. The higher resolution is achieved using the signal-to-noise-ratio (SNR). The higher the SNR, the better the resolution. Thus, these techniques are quite suitable for present day compact ranges where the noise level is typically very low. Specifically, we are looking at the MUSIC algorithm [49]. The MUSIC algorithm is an eigenvector based estimation technique. To use the algorithm, a covariance matrix is formed from the samples of the measured data. This measured data can be in the frequency domain or in the time domain. The eigenvectors and eigenvalues of this covariance matrix are then computed. The eigenvectors are separated into a set spanning the signal space and a set spanning the noise space. The down range (frequency domain data) or cross range (angle domain data) is then obtained by projecting a test vector onto the noise space. When the time delay in the test vector equals the time delay for a scattering center in the sample data, the test vector is orthogonal to the noise subspace. This algorithm has been applied to a number of real world situations with great success. For example, in the case of a 10" ogive, we were able to resolve the creeping wave term and the rear tip contribution for 40° look angle. The algorithm will be studied in more

detail to find the number of samples required for a given number of scattering centers. The effect of bandwidth and SNR on the resolution capability will also be studied. The ultimate goal of this study is to generate 3-dimensional images of a target using measured data.

4. Electromagnetic Scattering Analysis

a. Physical Optics Correction

The physical optics (PO) solution used to calculate the scattered fields from a conducting body leads to incorrect scattered fields even in the specular region. The inaccuracy stems from the fact that the surface currents used in the PO solution are incorrect near edges and at the shadow boundary of curved surfaces. In the case of edge structures, one can use the physical theory of diffraction (PTD) to correct the scattered fields. In the case of curved surfaces, the creeping wave term is the correction. The creeping wave represents a mechanism which propagates around the shadow boundary of the object. Thus, the erroneous term originating at the shadow boundary should be removed before adding the creeping wave term. We have developed mathematical expressions for the erroneous term. It has been found that for low observable targets, the erroneous term is quite significant. An efficient method to compute spurious end point contribution in PO solution has been developed. The method is applicable to general three-dimensional structures. The only information required to use the method is the radius of curvature of the body at the shadow boundary. Thus, the method is very efficient for numerical computations. The solution after removing the end point contribution is called the corrected PO solution. It has been shown that the corrected PO solution gives a

better approximation to the true scattered fields in the specular region. Further, it has been shown that the corrected PO can be used to compute the scattered fields from blended surfaces. In the case of blended surfaces, the radius of curvature and its first few derivatives are continuous at the junction between the surfaces.

b. Finite Difference Calculations

Finite difference calculations have been investigated for three dimensional surfaces using a "March in Time" approach developed by Bennett [31]. Results using this approach appears to be comparable to those generated by a conventional moment method approach for electrically small structures when tested using an ogive structure. The motivation for this approach is that it can readily calculate the scattered field frequency response for a structure and leads itself for vectorization on a supercomputer such as a Cray. Calculations using the Cray computer have been performed. Presently, the effort is towards plate structure to examine the edge wave scattering from corners. It is hoped to modify the technique into a hybrid to include GTD concepts to facilitate the calculation.

c. Electromagnetic Studies

The scattering from electrically large structures can originate from several mechanisms. Scattering from guided waves is one mechanism class that has not received significant attention. A common structure to support a guided wave is a crack or groove along a surface. The analysis of the propagation constant for such a wave was rigorously done by Shamansky [50]. From a scattering viewpoint, it is not merely the

existence of the guided wave but the termination of the crack from which the guided wave scatters. Measurements were performed to verify the analysis in [50]. Work is now under progress to analytically study the full three-dimensional scattering from cracks.

1. A.K. Dominek, L. Peters, Jr. and W.D. Burnside, "A Reflection Ansatz for Surfaces with Electrically Small Radii of Curvature," IEEE Transactions on Antennas and Propagation, Vol. AP-35, No. 6, June 1987.

   Uniform reflection coefficients are developed for two-and three-dimensional, edge-like, perfectly conducting surfaces in the deep lit region. The uniformity is with respect to the electrical size of the radii of curvature at the surface's specular point. This uniformity allows one to physically interpret the reflected field from a smooth surface as one of the radii of curvature approaches zero as a diffracted field. The coefficients are heuristically generated from the exact scattered field for a two dimensional parabolic cylinder with plane wave illumination. The significant variables in this solution are the radii of curvature at the specular point and the distance between the specular point and the incident shadow boundaries in the principal planes. The field prediction accuracy of these reflection coefficients are critically examined through comparisons with reflected fields extracted from scattered fields of canonical surfaces.

2. I.J. Gupta, C.W.I. Pistorius and W.D. Burnside, "An Efficient Method to Compute Spurious End Point Contributions in PO Solutions," IEEE Transactions on Antennas and Propagation, Vol. AP-35, No. 12, December 1987.

   A method is given to compute the spurious end point contributions in the physical optics (PO) solution for electromagnetic scattering from conducting bodies. The method is applicable to general three-dimensional structures. The only information required to use the method is the radius of curvature of the body at the shadow boundary. Thus, the method is very efficient for numerical computations. As an illustration, the method is applied to several bodies of revolution to compute the end point contributions for backscattering in the case of axial incidence. It is shown that in high frequency situations, the end point contributions obtained using the method are equal to the true end point contributions.

3. E. Shamansky and A. Dominek, "Compact Range Measurements of a Travelling Wave," AMTA Symposium Digest, Seattle, WA, September, 1987.

Many experimental and analytic studies on travelling waves have been performed in relation to their radiation properties for antenna applications. One common structure that has supported a fast travelling wave is a slotted waveguide. Such structures can also support traveling waves from a scattering viewpoint. This aspect was verified by incorporating a trough in an almond test body to observe its scattering characteristics using aspect angle patterns, frequency spectra and transient signatures from compact range measurements at the ElectroScience Laboratory, OSU. The travelling wave behavior is also correlated to the calculated travelling wave propagation constant for this structure with good agreement.

5. Antenna Studies

a. Microstrip Antenna Analysis

Our research in microstrip antennas has dealt with developing efficient techniques for analyzing the radiation and scattering from loaded rectangular microstrip antennas over a broad frequency range. A rectangular microstrip antenna is a rectengular metallic patch printed on an electrically thin grounded dielectric substrate. Microstrip antennas are almost always operated at first resonance, i.e., in a narrow frequency range where the length of the patch is about a half wavelength in the substrate medium. For this reason, most past work on microstrip antennas has concentrated on their behavior near first resonance. By contrast, we have been primarily interested in the scattering from microstrip antennas. In the scattering problem one cannot assume the incident radar will be at a frequency near first resonance, and thus it is necessary to be able to analyze the microstrip antenna over a broad frequency range at and above first resonance.

In the previous reporting period, we developed efficient techniques, and associated computer codes, for analyzing the scattering from a rectangular microstrip antenna over a broad frequency range. In brief the technique involves a method of moments solution of an integral equation for the current density on the microstrip patch [44]. The accuracy of the method was verified by comparison with measured RCS results versus frequency over a 5 to 1 bandwidth. It was found that the RCS of the microstrip patch consists of a number of large but narrow peaks. The RCS at the peaks can be larger than the physical area of the patch. The first peak is centered around the resonant frequency of the lowest order mode, however, there are other peaks centered around the resonant frequency of higher order modes.

One possible method for controlling the RCS of a microstrip antenna is through impedance loading. To study this problem we have added the ability to insert one or more lumped loaded between the microstrip patch and the ground plane. The code has also been modified so that it can analyze the radiation problem. That is, it can compute the input impedance and radiation pattern of a loaded microstrip antenna over a broad frequency range. It is found that resistive loading lowers the RCS and input impedance level of the microstrip antenna. A thesis describing the moment method solution for radiation and scattering from loaded microstrip antennas is now in preparation.

b. Slotline Antenna Analysis

A slotline or finline transmission is formed by a slit or aperture in a ground plane. If the slit is electrically thin, then a wave can propagate along the slit with essentially no radiation. A slotline

antenna is formed by gradually increasing the width of the slit. When the width is on the order of a half wavelength or more, significant radiation occurs from the open end of the line. Slotline antennas are typically printed on a thin (ungrounded) dielectric substrate. An advantage of slotline antennas is that they have the potential for wide bandwidth if properly fed. Slotline antennas are also extremely lightweight and may also have low scattering cross section. Thus, they may have application as a dish feed where it is desired to minimize feed blockage.

To better understand the slotline antenna, we are developing techniques for its analysis. These techniques are similar to those used for the microstrip antenna described above. Basically we are employing a method of moments solution for the currents on the metal plates printed on the dielectric substrate. The technique is sufficiently general to be able to treat various tapers (i.e., linear, exponential, etc.). At present we have analyzed the scattering from a slotline antenna, and verified the results by comparison with a conventional surface patch method of moments solution for plates in free space. The next step involves developing feed models for the slotline. When this is done we will be able to compute the input impedance and radiation patterns of the slotline antenna. As stated above, we will be considering different feeds, in order to find one which maximizes the bandwidth of the slotline antenna. We will also be looking at different tapers to see their effects on bandwidth and scattering cross section.

6. Inlet Scattering

An efficient hybrid procedure developed earlier [52], with the potential for analyzing the electromagnetic (EM) scattering from a class of realistic inlet configurations that can be modeled by joining piecewise separable waveguide sections was extended significantly under the NASA/Langley contract. A detailed description of this important extension, which was also referred to in the previous annual report, can be found in a 1986 technical report prepared by The Ohio State University ElectroScience Laboratory for NASA/Langley [35]. Specifically, this hybrid method combines the asymptotic high frequency techniques with the modal techniques, for determining in a a very simple fashion, the reflection and transmission coefficient associated with the junctions formed by the connection of the different piecewise separable waveguide sections comprising the open inlet cavity. A detailed study of the use of the modal fields and their modal rays for performing the asymptotic high frequency part of this analysis on a variety of separable waveguide shapes was completed through the support provided by NASA/Langley [35]. That work set the crucial foundation for developing the analysis and the codes, via other support, for predicting the scattering by 2-D and 3-D S-shaped rectangular inlet cavities with and without absorber coating interior walls [53]. In addition, a geometrical optics ray approach was also developed for predicting the scattering by a rectangular inlet with absorber lined interior walls [54]. All the codes developed to date including those mentioned above, for predicting the scattering by inlet cavities, have been delivered along with their user manuals to NASA/Langley during the present period. Further work in the area of inlet scattering on the NASA/Langley

support is presently being limited to some experimental verification of many of the codes developed thus far. These experiments are currently being planned with the inlet models presently available, and this work will continue into the next period.

The codes specifically delivered to NASA/Langley are for predicting:

(1) The EM scattering by perfectly-conducting rectangular and circular inlets with a simple planar impedance/dielectric termination. In the case of the circular inlet, a planar conducting blade structure with a hub termination can also be accommodated [52];

(2) The EM scattering by a special NASA/Langley inlet model [35];

(3) The EM scattering by a rectangular inlet with absorber lined interior lined walls [54]; and

(4) The EM scattering by a 2-D S-shaped inlet with absorber lined inner walls [53].

An extension of (4) to the 3-D case will be sent shortly when it is completed.

7. Antenna Cavity Scattering

The hybrid procedure for analyzing the EM scattering by inlet cavities, which was significantly extended under the NASA/Langley grant [35], appears to be potentially useful for the analysis of the scattering by regularly shaped antenna cavities as well [55]. The type of antenna cavities treated in [55] consisted of rectangular shapes in a ground plane and the cavities could be loaded with a dielectric material. This work which provided a highly efficient and physically

appealing analysis of the 2-D rectangular antenna cavities now being extended under NASA/Langley support to include the effects of simple 2-D antennas with loading, and then subsequently to include 3-D cavities with loaded antenna arrays inside.

First, the extension to analyze the radiation by simple electric and magnetic line sources in the 2-D analysis of the dielectric filled rectangular cavity has been performed during the present period. The solution for the radiation by sources in such a configuration retains the simplicity of the earlier solution obtained in [55] without the sources. It is noted that this relatively simple and efficient nature of the solution thus obtained is important for use in applications; such simplicity is not present in the numerical moment method solutions of this problem based on a mode matching or integral equation type formulation. In a sense we have obtained, using the hybrid asymptotic-modal procedure, a simple approximate but accurate and efficient Green's function for the problem; i.e., we have obtained the radiation by line sources within a dielectric filled rectangular cavity in a ground plane. Many accuracy tests have been performed recently, and more tests will be continued further for a variety of dielectric parameters, cavity dimensions, and different positions of the line sources. This solution will allow one to directly deal with slot or dipole type sources in the cavity. Presently, we are extending this solution to include the effects of waveguide fed slot antennas in the cavity when the cavity is excited by an external plane wave. The control of cavity scattering by loading the antennas will also be studied in the near future. All of this work will be extended later to deal with 3-D cavities for which the interior modes can be well defined. Furthermore, the dielectric filling

the entire cavity will also later be replaced by a planar dielectric radome or an FSS which does not fill the entire cavity to obtain more versatile solutions. The ultimate goal of this work is to develop a code for predicting the scattering by antenna cavities and for controlling the scattering by such cavities by optimizing the antenna loading.

8. Propfan Blade Scattering

Significant research has been done and is continuing to analyze the scattering from pusher and puller propfan blades. The effort is two fold being both an experimental and theoretical study. The study so far has centered around pusher blade applications but will follow into the puller blade applications.

RCS measurements of planar and three dimensional blades have been performed on a specially designed pusher forebody to quantify the level of returns, the scattering mechanisms involved and the similarities and differences between planar and three dimensional blades. The majority of the measurements have been static but dynamic (rotating blades assemblies) measurements have also been performed. The dynamic measurements will provide an alternate approach to accurately measure the propfan RCS.

RCS calculations of planar and three dimensional blades are presently being performed as a GTD based computer code is being developed. The code will be able to calculate the scattering from a single blade or blade assembly on a forebody structure. The description of the blades are analytically defined to facilitate the required computational requirements and graphical display of the blades

computational requirements and graphical display of the blades geometry. The graphical display conveniently indicates the geometry of the blade, and its shadowing from and to other blades as well as the forebody.

9. Miscellaneous Measurements

a. Surface Conductivity

RCS model measurements often have to be coated to provide a conductive surface. The conductive quality of these coatings can affect such measurements. A series of rectangular cross section inlets were built to measure the influence of conductive coatings on the RCS from a structure. This structure was chosen because an accurate GTD solution exists for both the structure and cavity scattering to provide a perfectly conducting reference solution. This structure provides an accurate indicator of the loss characteristics of the paint because the larger off axis angles involve many modal reflections. The inlets were fabricated from fiberglass and had an external surface coating of silver. The internal surfaces of the inlets were coated with air sprayed paints or arc sprayed with metal. The metals examined were silver, copper, nickel and zinc. The silver paint was superior and agreed very well with the calculation with the nickel paint being the next best followed by the copper paint. The zinc arc sprayed coating had a similar performance as did the nickel air sprayed paint.

b. Images

A new scheme to generate two-dimensional images of scattering centers was reported in the last year's final report. This scheme has been expanded to produce three dimensional images as well. This

technique entails the processing of downrange, bandlimited impulse responses for two look angles in the horizontal plane for the horizontal cross range location of the scattering centers and for two look angles in the vertical plane for the vertical cross range location of the scattering centers. The two look angles illuminate the targets with plane waves at slightly different angles. The returns from these two look angles are paired together and the cross range location of the scattering centers is obtained from the relative downrange offset between the average downrange location and the individual returns. High resolution techniques are also being applied to minimize the required bandwidth.

c. Starbody

RCS measurements were performed on a new forebody design for high speed aircraft. This forebody could be crudely represented by a cone with fins radially expanding from the tip to the base. Two versions were tested with one having the fins expanding in a plane containing the cone's axis and the other having the fins spiraling outward. The scattering performance of either design was less than desirable. The expanding fin structure at the tip of the cone created a larger scattering center. The spiral fin feature of one design presented the existence of specular returns much earlier than the other design.

d. Recent Publications

1. A. Dominek, H. Shamansky, R. Burkholder, R. Wood, and W. Hodges, "A Method of Evaluating Conductive Coatings for RCS Models," AMTA Symposium Digest, Seattle, WA, September, 1987.

A novel method for evaluating conductive coatings used for radar cross section (RCS) scale models is presented. The method involves the RCS measurement of a short circuited cavity whose interior is coated with the material under study. The dominant scattering from such a structure occurs from the cavity rim and surface walls internal to the cavity. The method of conductivity testing has excellent sensitivity due to the energy that couples in and out of the cavity. this energy undergoes many reflections with the interior walls and thus very small losses can be detected. Calculations and measurements are shown for several different types of coatings, including coatings of silver, copper nickel and zinc.

REFERENCES

[1] F.A. Sikta, "UTD Analysis of Electromagnetic Scattering by Flat Plate Structures," Report 711930-2, The Ohio State University ElectroScience Laboratory, prepared under Grant NSG-1613 for NASA-Langley Research Center, Hampton, Virginia, December 1981.

[2] I.J. Gupta and W.D. Burnside, "Physical Optics Correction for Backscattering from Curved Surfaces," in IEEE Transactions on Antennas and Propagation, May 1987.

[3] E.H. Newman and R.L. Dilsavor," A User's Manual for the Electromagnetic Surface Patch Code: ESP Version III," Report 716148-19, The Ohio State University ElectroScience Laboratory, prepared under Grant NSG-1613 for NASA-Langley Research Center, May 1987.

[4] Vaturu Ebihara and R.J. Marhefka, "Bistatic Scattering from a Cone Frustum," Report 716148-16, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, August 1986.

[5] J.L. Volakis, "Electromagnetic Scattering from Inlets and Plates Mounted on Arbitrary Smooth Surfaces," Report 711930-5, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, August 1982.

[6] A.K. Dominek, "A Uniform Electromagnetic Reflection Ansatz for Surfaces with Small Radii of Curvature," Ph.D. Dissertation, The Ohio State University, Department of Electrical Engineering, 1984.

[7] R.L. Barger, "A Procedure for Designing Forebodies with Constraints on Cross-Section Shape and Axial Area Distribution," NASA Technical Paper 1881, Langley Research Center, 1981.

[8] T.T. Chu, "First Order Uniform Theory of Diffraction (UTD) Analysis of the Scattering by Smooth Surfaces," Final Report 711930-6, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, April 1983.

[9] R.H. Campbell, "Electromagnetic Backscatter from a Flat Plate in the Vicinity of a General Curved Surface," Master's Thesis, the Ohio State University, Department of Electrical Engineering, 1984.

[10] C.W.I. Pistorius, "An Envelope Description of the Backscattered Power Patterns of Conducting Bodies," Master's Thesis, The Ohio State University, Department of Electrical Engineering, 1984.

[11] E.H. Newman, P. Alexandropoulos and E.K. Walton, "Polygonal Plate Modeling of Realistic Structures," IEEE Transactions on Antennas and Propagation, Vol. AP-32, No. 7, July 1984.

[12] R. Whitacre, "The OSU Pulse/CW Radar for Compact Range Radar Cross Section Measurements," M.Sc. Thesis, The Ohio State University, Department of Electrical Engineering, August 1985.

[13] D.N. Jones, W.D. Burnside, "A Very Wide Frequency Band Pulsed/IF Radar System," Report 716148-28, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, March 1988.

[14] W.D. Burnside, P. Bohley and D. Jones, "A Broadband, Inexpensive, Ka-band Pulsed Radar System," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

[15] A. Lai and W.D. Burnside, "Monostatic and Bistatic Scattering by Metal Ogival Target Support," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

[16] W.D. Burnside, M.C. Gilreath, B.M. Kent and G.L. Clerici, "Curved Edge Modification of Compact Range Reflector," IEEE Transactions on Antennas and Propagation, Vol. AP-35, No. 2, February 1987.

[17] C.W.I. Pistorius and W.D. Burnside, "The Design of Blended Rolled Edges for Compact Range Main Reflectors," Fifth International IEE Conference on Antennas and Propagation, University of York, UK, March 30-April 2, 1987.

[18] C.W.I. Pistorius and W.D. Burnside, "A Concave Edged Reflector with Blended Rolled Surface Terminations for Compact Range Applications," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

[19] C.W.I. Pistorius, "New Main Reflector, Subreflector and Dual Chamber Concepts for Compact Range Applications," Ph.D. Dissertation, The Ohio State University, December 1986.

[20] I.J. Gupta and W.D. Burnside, "User Manual for Semi-Circular Compact Range Reflector Code," Tech. Report 716148-18, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, January 1987.

[21] W.D. Burnside, R.C. Rudduck, I.J. Gupta and J. Clerici, "Electromagnetic Performance Study of Scientific-Atlanta's New Compact Range," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

[22] D.J. Heedy, "An E-Plane Analysis of Aperture-Matched Horn Antennas Using the Moment Method and the Uniform Geometrical Theory of Diffractions," Master's Thesis, The Ohio State University, Department of Electrical Engineering, 1984.

[23] B.T. DeWitt, "Analysis and Measurement of Electromagnetic Scattering by Pyramidal and Wedge Absorbers," Ph.D. Dissertation, The Ohio State University, Department of Electrical Engineering, 1986.

[24] A.K. Dominek, W.D. Burnside and L. Peters, Jr., "Mechanism Extraction," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

[25] P.H. Pathak, W.D. Burnside and R.J. Marhefka, "A Uniform GTD Analysis of the Diffraction of Electromagnetic Waves by a Smooth Convex Surface," IEEE Transactions on Antennas and Propagation, Vol. AP-28, pp. 631-642, September 1980.

[26] A.A. Ksienski, "A Method of Resolving Data into Two Maximally Smooth Components," Proceedings of IEEE, Vol. 73, No. 1, January 1985.

[27] L. Peters, Jr., R.T. Swann and W.T. Hodges, "An Experimental Investigation of Electromagnetic Scattering Properties of Flat Composite Structures," Tech. Report 716148-2, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, October 1984. (Classified Report)

[28] L. Peters, Jr., A.K. Dominek, R. Swann, W.T. Hodges and S. Wozniak, "Edge Wave Control Using Absorber on Composite Material," Report 716148-15, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, July 1986. (Classified Report)

[29] E.H. Newman, R.J. Marhefka and L. Peters, Jr., "Scattering from Nearly Flat Surfaces or Nearly Straight Edges," "Report 716148-17, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, October 1986. (Classified Report)

[30] A.K. Dominek, H.T. Shamansky, R. Wood and R. Barger, "A Useful Test Body," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

[31] C.L. Bennett and R. Hieronymus, "Space-Time Integral Equation Approach to Solution of Plane Symmetric Scattering Problems," Report SCRC-CR-75-9, Sperry Research Center, May 1975.

[32] R.C. Rudduck and T.H. Lee, "Reflector Antenna Code" under development for National Aeronautics and Space Administration, Langley Research Center.

[33] R.C. Rudduck, W.D. Burnside, A.K. Dominek and T.H. Lee, "Simulation of an Aircraft Flying Through A Ground Station to Satellite Link," Technical Report 716148-7, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, February 1986.

[34] W.D. Burnside, R.C. Rudduck, A.K. Dominek and T.H. Lee, "Simulation of an Aircraft Flying Through a Ground Station to Satellite Link," AMTA Symposium Digest, Ottawa, Canada, September 23-25, 1986.

[35] A. Altintas, P.H. Pathak and W.D. Burnside, "Electromagnetic Scattering from a Class of Open-Ended Waveguide Discontinuities," Technical Report 716148-9, The Ohio State University ElectroScience Laboratory, prepared under Grant NGS-1613 for NASA-Langley Research Center, Hampton, VA, March 1986.

[36] A. Altintas, "Electromagnetic Scattering from a Class of Open-Ended Waveguide Discontinuities," Ph.D. Dissertation, The Ohio State University, Department of Electrical Engineering, 1986.

[37] R.J. Burkholder, "High Frequency Backscatter Analysis of Electrically Large Inlets," Master's Thesis, The Ohio State University, Department of Electrical Engineering, 1985.

[38] E.H. Newman, "Strip Antennas in a Dielectric Slab,", IEEE Transactions on Antennas and Propagation, Vol. AP-26, pp. 746-653, September 1978.

[39] E.H. Newman and P. Tulyathan, "Analysis of Microstrip Antennas Using Moment Methods," IEEE Transactions on Antennas and Propagation, Vol. AP-29, pp. 47-54, January 1981.

[40] E.H. Newman, J.H. Richmond and B.W. Kwan, "Mutual Impedance Computation Between Microstrip Antennas," IEEE Trans. Microwave Theory and Tech., Vol. MTT-31, pp. 941-945, November 1983.

[41] E.H. Newman and J.E. Tehan, "Analysis of a Microstrip Array and its Feed Network," IEEE Transactions on Antennas and Propagation, Vol. AP-33, pp. 397-403, April 1985.

[42] B.W. Kwan, E.H. Newman and R.G. Kouyoumjian, "Mutual Coupling Between Microstrip Modes on a Dielectric Coated Cylinder," IEEE Transactions on Antennas and Propagation, in preparation.

[43] B.W. Kwan, R.G. Kouyoumjian and E.H. Newman, "An Asymptotic Evaluation of the Mutual Impedance Between 2-D Strips on a Dielectric Coated Circular Cylinder," IEEE Transactions on Antennas and Propagation, in preparation.

[44] E.H. Newman and F. Forrai, "Scattering from a Microstrip Patch," IEEE Transactions on Antennas and Propagation, Vol. AP-35, March 1987.

[45] E.H. Newman, and D.M. Pozar, "Electromagnetic Modeling of Composite Wire and Surface Geometries," IEEE Transactions on Antennas and Propagation, Vol. AP-26, pp. 784-789, November 1978.

[46] E.H. Newman and D.M. Pozar, "Considerations for Efficient Wire/Surface Modeling," IEEE Transactions on Antennas and Propagation, Vol. AP-28, pp. 121-125, January 1980.

[47] D.M. Pozar and E.H. Newman, "Analysis of a Monopole Mounted at or Near the Edge of a Wedge," IEEE Transactions on Antennas and Propagation, Vol. AP-29, pp. 488-495, May 1981.

[48] D.M. Pozar and E.H. Newman, "Analysis of a Monopole Mounted Near an Edge or a Vertex," IEEE Transactions on Antennas and Propagation, Vol. AP-30, pp. 401-408, May 1982.

[49] R.O. Schmidt, "Multiple Emitter Location and Signal Parameter Estimation," IEEE Transactions on Antennas and Propagation, Vol. AP-34, No. 3, pp. 276-280, March 1986.

[50] H. Shamansky, "The Determination of the Propagation Constant for the Travelling Wave in a Trough in an Infinite Ground Plane," Master's Thesis, The Ohio State University, Department of Electrical Engineering, 1987.

[51] D. Forrai, "Analysis of the Radiation and Scattering from a Loaded Microstrip Antenna over a Broad Frequency Range," M.S. Thesis, The Ohio State University, Department of Electrical Engineering, in preparation.

[52] P.H. Pathak, C.W. Chuang, and M.C. Liang, "Inlet Modeling Studies," Technical Report 717674-1, The Ohio State University ElectroScience Laboratory, prepared under Contract No. N60530-85-C-0249 for naval Weapons Center, China Lake, CA, October 1986.

[53] R.J. Burkholder, C.W. Chuang and P.H. Pathak, "Electromagnetic Fields Backscattered from an S-shaped Inlet Cavity with an Absorber Coating on its Inner Walls," Final Report 715723-2, The Ohio State University ElectroScience Laboratory, prepared under Grant No. NAG3-476 for NASA/Lewis Research Center., Cleveland, OH, July 1987.

[54] N.H. Myung, P.H. Pathak, "A High Frequency Analysis of Electromagnetic Plane Wave Scattering by Perfectly Conducting Semi-Infinite Parallel Plate and Rectangular Waveguide with Absorber Coated Inner Walls," Technical Report 715723-1, The Ohio State University ElectroScience Laboratory, prepared under Grant NAG 3-476, for NASA/Lewis Research Center, Cleveland, Ohio September 1986.

[55] M.C. Liang, P.H. Pathak and C.W. Chuang, "An Efficient Hybrid GTD-Modal Analysis of the Scattering by an Open-Ended Dielectric Filled Cavity in a Ground Plane", Report No. 716611-2, The Ohio State University ElectroScience Laboratory, prepared under Contract F33615-84-K-1550, Air Force Systems Command, Aeronautical Division, Wright-Patterson AFB, OH 45433, July 1987.